

The $\dot{M} - M$ relationship in pre-main sequence stars

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ABSTRACT

We examine the recent data and analysis of Natta et al. concerning the accretion rate on to young stars as a function of stellar mass, and conclude that the apparently steep dependence of accretion rate on mass is strongly driven by selection/detection thresholds. We argue that a convincing demonstration of a physical relationship between accretion and stellar mass requires further studies which, as is the case for Natta et al., include information on upper limits, and which quantify the possible incompleteness of the sample, at both low and high accretion rates. We point out that the distribution of detections in the (M, \dot{M}) -plane can in principle be used to test conventional accretion disc evolutionary models, and that higher sensitivity observations might be able to test the hypothesis of accelerated disc clearing at late times.

Key words: Accretion, accretion discs - stars: pre-main sequence - stars: low-mass, brown dwarfs - planetary systems:protoplanetary discs

1 INTRODUCTION

There appears to be increasing acceptance that the accretion rate, \dot{M} , onto pre-main sequence stars, although it shows a large scatter, correlates roughly as the square of the stellar mass, M (Muzerolle et al 2003; Natta et al 2004; Calvet et al 2004; Muzerolle et al 2005; Mohanty et al 2005; Natta et al 2006). From a theoretical point of view this is a somewhat surprising finding in that it appears to indicate that the accretion processes at different masses do not scale simply with mass. It has been interpreted variously as indicating that accretion is Bondi-Hoyle accretion in a uniform environment (Padoan et al., 2005) or as giving us information about the initial conditions established when the discs form (Alexander & Armitage, 2006; Dullemond, Natta and Testi, 2006).

The recent compilation of Natta et al. (2006) however permits us to examine this claim more quantitatively than has been possible hitherto. Our analysis here suggests that the distribution of stars in the plane of accretion rate versus mass is largely bounded by detection and selection thresholds and that the claimed steep relationship between accretion rate and mass is then an inevitable consequence of these thresholds. We, however, stress that we in no way rule out the possibility that mean accretion rate is a steep function of stellar mass, but instead set out the conditions that must be satisfied by future datasets before this claim can be taken at face value.

2 MEASUREMENTS, UPPER LIMITS AND CORRELATIONS

The possibility that there is a strong correlation between accretion rate and stellar mass was noted by Muzerolle et al. (2003), who assembled accretion rate estimates obtained through a variety of diagnostics (fitting of emission line profiles, veiling measurements, determination of U band excesses: see Figure 8 of Muzerolle et al., 2003). In order to make a critical assessment of this claim, however, it is necessary to work with a well-defined, homogeneous sample for which the accretion rate is measured in a uniform manner. The recent dataset of Natta et al. (2006) in the core of ρ Oph satisfies these criteria and in addition, and very valuably, lists the upper limits for non-detections.

In Figure 1, we plot the detected measurements of accretion rate, together with the upper limits, as a function of stellar mass (see also Natta et al., 2006, Figure 2).¹ It is immediately evident, first, that the upper limits also correlate with mass in the same way as the detections, and, second, that the upper limits and detections overlap at each value of M . It is therefore clear that the observed $\dot{M} - M$ relation is being strongly driven by detectability limits in the (\dot{M}, M) -plane.

The reason for the strong correlation between de-

¹ Note that in the interests of uniformity of analysis we use only measurements based on Pa β and omit the eleven objects for which only Br γ measurements are available

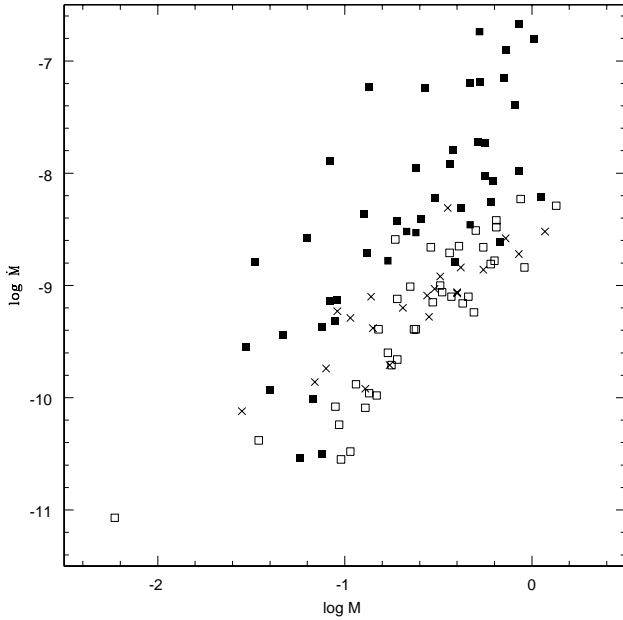


Figure 1. Accretion rate is plotted against stellar mass for data points derived from Pa β in Natta et al. (2006). Filled squares are measurements, and open squares are upper limits for Class II objects. Crosses are upper limits for Class III objects.

tectability of accretion rate and mass is easy to understand and results from a combination of two effects. First, Natta et al. (2006) make the reasonable assumption the the observed stars fall on an isochrone. This assumption implies that there are therefore strong correlations between luminosity, L , and mass (Figure 2) and between radius, R , and mass (Figure 3) for the stars in the dataset. We should note that even if this assumption is relaxed, and an attempt is made to estimate masses and radii by placing the stars on pre-main sequence tracks in the HR diagram, because all the stars observed are of a similar age, all other datasets show similar, although not so tight, correlations. For the Natta et al. (2006) dataset we find roughly that $L \propto M^{1.7}$ and $R \propto M^{0.6}$. Second, Natta et al. (2006) use the equivalent width of the Pa β line as their primary indication of accretion rate. What this means in effect is that, in line with all other methods, accretion rate is estimated by measuring extra flux of some kind over and above that expected for the stellar photospheric (including chromospheric) flux for the star in question. Thus to first order, all estimates of accretion rate rely essentially on estimating the dimensionless quantity

$$k = \frac{L_{\text{acc}}}{L}, \quad (1)$$

where

$$L_{\text{acc}} = \frac{GM\dot{M}}{R}, \quad (2)$$

is the accretion luminosity.

From these relations we see that

$$\dot{M} = \frac{kRL}{GM}. \quad (3)$$

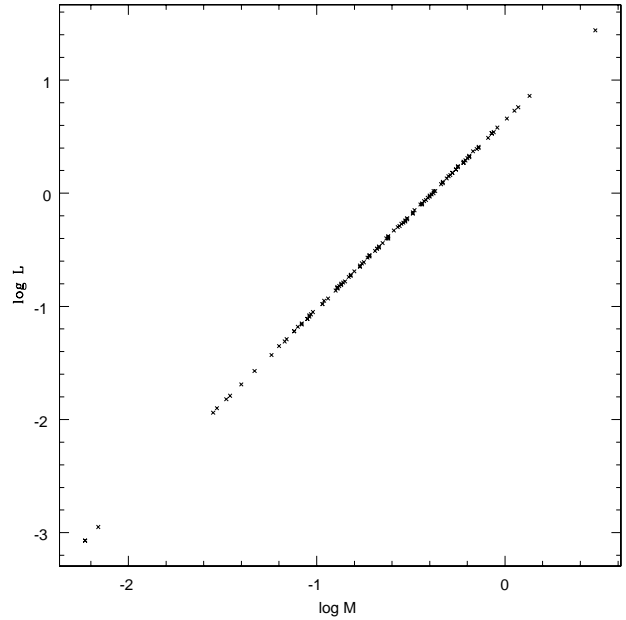


Figure 2. The assumed luminosity-mass relation for the stars in the Natta et al (2006) sample.

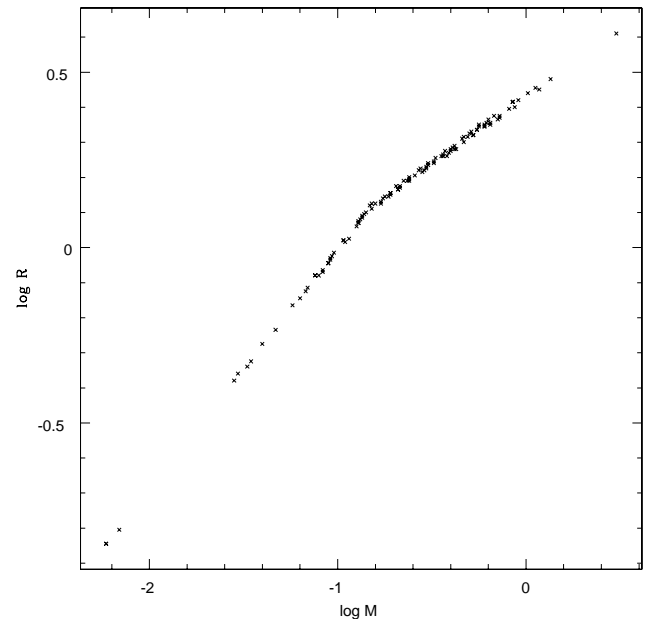


Figure 3. The assumed radius-mass relation for the stars in the Natta et al. (2006) sample.

We plot k as a function of M for the Natta et al. (2006) data in Figure 4 (see also their Figure 2). The plot displays considerable scatter in k at a given mass (more than two orders of magnitude). The regions of the plot that are filled with points are simply bounded by detection limits - e.g. the observed values of k are all less than unity since accretion rates are not readily determinable in the case that the

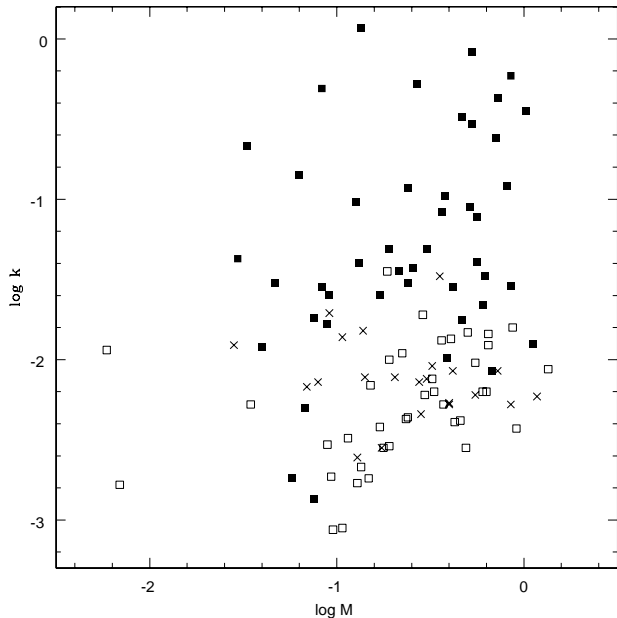


Figure 4. The value of $k = L_{\text{acc}}/L$ plotted against stellar mass for data points derived from Pa β in Natta et al. (2006). Filled squares are measurements, and open squares are upper limits for Class II objects. Crosses are upper limits for Class III objects.

accretion rate exceeds the stellar luminosity (Hartmann et al., 1998). In addition, there is an apparent mild slope to the lower boundary of the distribution, i.e. an absence of detections in the lower right portion of the diagram. This however is also explicable as a sensitivity issue, since the upper limits follow the same trend. We therefore conclude that the detectable region of (k, M) parameter space is rather uniformly populated with detections. At fixed k , the correlations between M , R and L imply $\dot{M} \propto M^{1.3}$. We can therefore see that if the detectable region of (M, k) parameter space were roughly uniformly populated with detections, in some range $k_1 < k < k_2$ and $M_1 < M < M_2$, then the tightness of the $R - M$ and $L - M$ correlations would give a spurious correlation between \dot{M} and M .² In our case because there is a mild positive slope to the lower bound of the detectable region in the (M, k) -plane, the detected systems necessarily exhibit a correlation between accretion rate and mass that is somewhat steeper than $\dot{M} \propto M^{1.3}$.

3 DISCUSSION

3.1 The lack of high accretion rates at low masses

We have argued above that that maximum values of accretion rate at all masses all correspond roughly to the case that the accretion luminosity is comparable with the stellar luminosity ($k \approx 1$), and that this could just be an observational selection effect. For example, in the case of Taurus,

² This is analogous to the well known phenomenon that even if the two quantities A and B are uncorrelated, the quantities $Af(B)$ and B can in fact appear correlated.

Kenyon and Hartmann (1995) classified six stars as ‘continuum stars’, where the level of veiling was so high as to fill in the photospheric absorption lines. It is an important matter to establish the number of systems that could have been missed in the present sample.

If, in reality, there are few objects that have been systematically excluded on account of high accretion rate ($k > 1$), then there appears to be lack of systems in the upper left of Figure 1. In this case, we need to enquire whether this lack is statistically significant given the present sample. In other words, we need to determine if the null hypothesis (viz. that the distribution of \dot{M} is independent of M) is contradicted by the data.

We analyse this issue by splitting the data mass into two mass bins, with $M < M_c$ and $M > M_c$, for some mass M_c . and then using a modified version of the Kolmogorov–Smirnov (KS) test. If we had accretion rate measurements for all the objects studied (rather than just upper limits for some), then we would apply the KS test by computing the cumulative distributions of \dot{M} in the two mass bins, by finding the largest difference between these two distributions, and by then using the KS statistic to assess the significance of this difference. In the current case, however, a number of the data points are upper limits, rather than actual measurements. But since the upper limits in Figure 1 are all at accretion rates $\log \dot{M} < -8.1$, we can still measure the greatest difference between the two cumulative distributions in the domain $\log \dot{M} > -8.1$, and then use the KS test to assess the significance of that difference. Note that since the actual difference (had we been able to measure all the values of \dot{M}) is greater than this, this procedure in fact underestimates the significance of the difference between the two distributions. We have undertaken this analysis using a number of trial values of M_c and find that if we split the sample at $\log M_c = -0.5$ (i.e. at $M_c = 0.3M_\odot$) the KS probability is around 0.04, i.e. we can rule out the null hypothesis at about the 2σ level. Small changes in the value of M_c (i.e. by 0.1 dex) however increases the KS probability and renders the difference insignificant at the 2σ level.

We therefore conclude that, *if* there are in reality no systems that have been systematically excluded on account of excessively large accretion rates, then the difference in accretion rate distribution at high and low mass is marginally statistically significant.³ This result is independent of any issues relating to the mass dependence of the lower detection limits, owing to the way that we have included the upper limits in our analysis. Larger samples should be able to improve the statistical significance of this result and make it less sensitive to exactly where the mass cuts are taken. We stress that such analysis can only be conducted using samples which, like that of Natta et al. (2006), both contain data acquired in a uniform fashion and which include all the information on upper limits for non-detections.

³ If, however, we perform a similar analysis on the quantity \dot{M}/M , implying a null hypothesis that $\dot{M} \propto M$, we find no significant difference between the distributions in different mass bins. Thus $\dot{M} \propto M$ is consistent with the data.

3.2 What does the distribution in the $\dot{M} - M$ plane tell us?

The distribution of detections in the $\dot{M} - M$ plane yields information about the relative amounts of time that systems spend in various regions of that plane. In fact, since the mass of a star changes negligibly during the Class II phase, this plot is mainly a diagnostic tool for the evolution of \dot{M} during this phase. Simple disc models generally predict that \dot{M} should decline as a power law of the time, in which case the number of objects found in equal intervals of $\log \dot{M}$ should increase somewhat at lower \dot{M} .⁴ In principle, one could split the sample according to stellar mass and then use the distribution of accretion rates to test the hypothesis of power law decline of \dot{M} with time, and measure its exponent. The current dataset is however too sparse to permit this exercise.

The scarcity of T Tauri stars with infrared colours that are intermediate between those of Class II and Class III sources (see Kenyon and Hartmann, 1995; Simon and Prato, 1995) however indicates that there may at some point be a rapid evolution in \dot{M} , i.e. ‘two timescale’ behaviour that is incompatible with a simple power law decline (Armitage, Clarke & Tout, 1999; Clarke, Gendrin & Sotomayor, 2001). This behaviour would be manifest as a lack of points below some (possibly mass dependent) accretion rate. There is no evidence for such behaviour in the current dataset since the lowest detection and upper limits are inter-mingled, and the same is true of accretion rates based on veiling and U band measurements (see White and Ghez, 2001). Even in the case of the most sensitive accretion rate measurements (obtained via modeling H α emission lines profiles in brown dwarfs), the lowest detected rates are within a factor two of the estimated sensitivity limit (Muzerolle et al., 2003), which, given the uncertainties of $\sim 3-5$ in the derived rates, cannot be taken as evidence for a gap.

The predicted accretion rates at which rapid evolution should set in are however very low. In ‘ultraviolet switch’ models for disc dispersal (Clarke et al., 2001; Alexander, Clarke & Pringle, 2006a,b), the accelerated dispersal occurs when the accretion rate becomes comparable with the rate of photoevaporation by the star’s ionising flux, which is estimated to be $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$ for solar mass stars (Hollenbach et al., 1994; Alexander, Clarke & Pringle, 2005). This rate scales with the square root of the product of stellar mass and ionising flux, so that *if* the ionising flux simply scales with stellar luminosity, the critical \dot{M} scales as $\propto M^{1.35}$. However the sharp drop in chromospheric activity in late type stars (Dobler, Stix & Brandenburg, 2006) suggests that the critical \dot{M} might scale more strongly with mass. Evidently these accretion rates are not measurable with current data. Alternatively, it is often assumed that the rapid transition in infrared colours is instead associated with grain growth in the inner disc (e.g. Sicilia-Aguilar et al., 2006), in which case one might not expect any deviation

⁴ There are however individual cases where the accretion timescale ($t_{\text{acc}} = M_{\text{disc}}/\dot{M}$) is apparently less than the stellar age, a result that is most easily explained in terms of fluctuating accretion rates (see Scholz and Jayawardhana, 2006, and Littlefair et al., 2004, for evidence that some T Tauri stars show pronounced changes in spectral characteristics).

from power law decline in accretion rate with time at low \dot{M} . Future high sensitivity observations could thus in principle distinguish between these possibilities. It should however be noted that, in future experiments, the outcome should not be prejudiced by throwing out of the sample those objects that are deemed in advance to be non-accretors (see Muzerolle et al., 2003, and Mohanty et al., 2005, for details of pre-selection of possible accretors based on H α equivalent widths).

4 CONCLUSION

We have shown that the $\dot{M} - M$ measurements of Natta et al. (2006) are bounded by the conditions $L_{\text{acc}} \sim L$ at high \dot{M} and by a lower bound that is defined by the locus of upper limits in this plane. The region bounded by these detection/selection thresholds is filled rather uniformly by detections and the slopes of these thresholds are such that the detections exhibit a steep dependence of mean \dot{M} on M . A conservative interpretation is therefore that current data cannot be used to demonstrate a *physical* correlation between accretion rate and stellar mass.

A number of interesting points should be borne in mind for future investigations.

- i) If the absence of systems with $L_{\text{acc}} > L$ is real (i.e. not a selection bias) then the null hypothesis that accretion rate is independent of mass can be marginally rejected at about the 2σ level. Larger samples are required in order to demonstrate the statistical significance of this result.
- ii) Within the regions of detectability, stars are roughly uniformly distributed in $\log \dot{M}$. Such behaviour is compatible with a power law decline in accretion rate with time, as predicted by conventional accretion disc models.
- iii) Higher sensitivity measurements across a range of masses could in principle establish whether there are empty regions at low accretion rates, corresponding to a phase of rapid disc clearing (as, for example, in photoevaporation models).

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